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ACES RED Experiment #1 Environmental Test Results for Industrial Grade, Non-traditional, and Other Components Lacking Flight Heritage

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Abstract

Results of the thermal vacuum chamber (TVAC) testing and vibrational testing of the ACES RED Experiment #1 are presented. Performance of commercial-off-the-shelf components such as the Avnet PicoZed, the Xiphos Q7, the MAI-400, and a NovaTel GNSS during TVAC testing are provided and analyzed. To our knowledge, this is the first orbital flight of this version of the GNSS, this version of the MAI-400, and the PicoZed. The experiment utilizes a novel structural concept for ease of electronics assembly and disassembly. The health monitoring system measures temperatures, vibration, voltages, and currents for situational awareness of each of these component's relative performance. An assessment and progression of the technology readiness level of the hardware is also presented.

Introduction

The Army Cost-Efficient Spaceflight Research Experiments and Demonstrations (ACES RED) is an iterative, periodic flight experiment and demonstration effort to test singular phenomena, technologies, and concepts for future Science and Technology (S&T) projects that are directly related to and in support of the United States Army Space S&T Roadmap Programs. The first ACES RED experiment, AR#1, or the Attitude Determination and Control System (ADCS) Flyer, has a main focus to expand on the available dataset to verify long-duration performance as well as mature various commercial-off-the-shelf (COTS) technologies that will reduce the cost and complexity while maintaining or improving performance of Army small satellites. AR#1 has a primary focus on attitude determination and control components.

The primary payload is an MAI-400 ADCS. Secondary and tertiary payloads include: FPGA-based flight computers, low cost flight computers (Avnet PicoZed, Atmel microcontroller), global positioning system, low cost star-tracker, and various internal vehicle diagnostic sensors. The experiment will be mounted on the Department of Defense Space Test Program's STP-H6 pallet on the International Space Station (ISS) ELC-3 (ExPRESS Logistics Carrier-3) with operation and access to continuous on-orbit data for greater than one year with reliable reference instrumentation. Because of the nature of the launch and the ISS mission, NASA requirements must be met. Among these requirements include both individual and integrated-level environmental testing, including both thermal vacuum (TVAC) and vibrational tests. Additional information on the mission and objectives can be found in [1].

As mentioned in our previous publication, one of our objectives is to increase the Technology Readiness Level (TRL) of several components. We loosely base our assessment on the NASA definitions [2] and Table 1, as commercial-off-the-shelf and other industrial grade or non-traditional components do not quite fit the typical transition of TRL. The AR #1 demonstration has been published in prior proceedings and thus we considered the design at TRL 1 as of August 2017. Through Mission Readiness, Preliminary, and subsequent Critical Design and other associated formalized reviews, thorough documentation with descriptions of the design outlining feasibility and benefit had been concluded as of September 2017, we consider TRL 2 to have been achieved for the hardware and some of the software aspects of the experiment.

An on-site demonstration/test of the NASA and STP hardware and software interfaces was performed and documented at the Kennedy Space Center in February 2018, and thus we have achieved both TRL 3 & 4 for the hardware and software. Subsequently, the flight hardware was tested in a thermal vacuum chamber and on a vibe table concluding on 6 April 2018, the results of which are documented and presented in the following sections.

Table 1: NASA Technology Readiness Level Definitions [2]

TRL	Definition	Hardware Description	Exit Criteria
1	Basic principles observed and reported.	Scientific knowledge generated underpinning hardware technology concepts/applications.	Peer-reviewed publication of research underlying the proposed concept/application.
2	Technology concept and/or application formulated.	Invention begins, practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.	Documented description of the application/concept that addresses feasibility and benefit.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Analytical studies place the technology in an appropriate context and laboratory demonstrations, modeling and simulation validate analytical prediction.	Documented analytical/experimental results validating predictions of key parameters.
4	Component and/or breadboard validation in laboratory environment.	A low fidelity system/component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to the final operating environment.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of relevant environment.
5	Component and/or breadboard validation in relevant environment.	A medium fidelity system/component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrates overall performance in critical areas. Performance predictions are made for subsequent development phases.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements.

The following sections present the results from the tests. Several rounds of testing were performed. The first round was leveraged to determine the nuances associated with the testing and any other pertinent information required to determine that our test article met the specifications required for the STP-H6 mission.

Design Overview

AR #1 utilizes a unique design scheme not often found within the space community. Many CubeSats™ utilize a "stacking" method of placing the various hardware boards and components on top of each other, creating an array of flight computers, power boards, etc[1,2,3,4]. This limits the engineer if a board within the stack malfunctions or fails. The satellite integrator would need to remove the subsequent items in the stack in order to reveal the problematic board. AR#1 was designed to avoid this issue by developing a modular design, leveraging a sort of "plug and play" system that would allow components to be changed without having to remove the rest of the stack.

The final iteration of this design is a "modular tray" system. Slots with standardized dimensions were created at specific points within the AR#1 frame that accept modular trays to which hardware components are mounted. The trays were designed to insert securely into the frame of AR#1 and to fit any of the standard slots, allowing the trays to be interchanged at any time, regardless of the hardware, and re-insert into the frame at a different position.

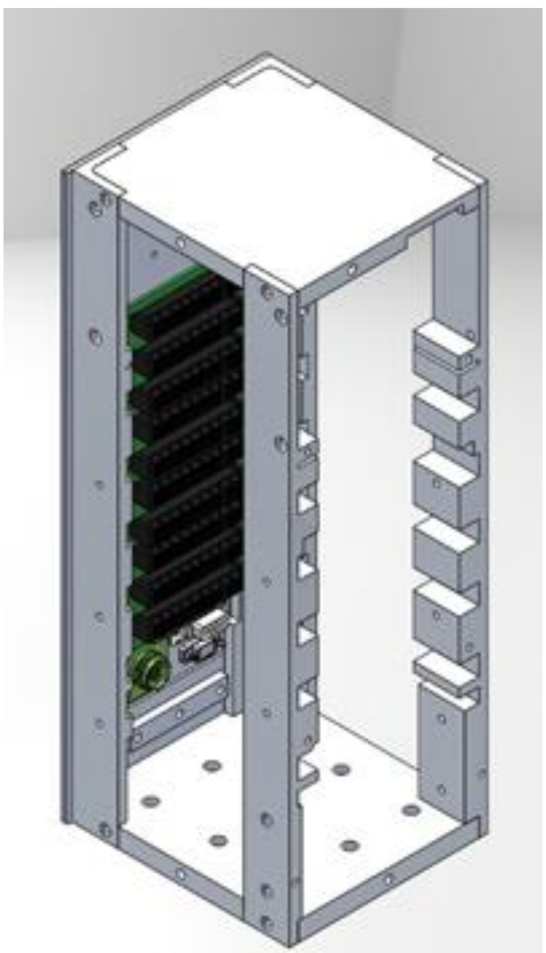

Figure 1: ACES RED Experiment #1 Frame

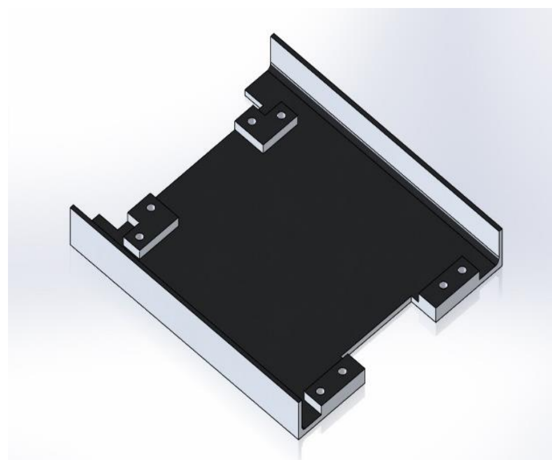

Figure 2: ACES RED Modular Tray

TVAC Test Overview

The TVAC (thermal vacuum) testing consisted of several phases, namely, pre-test bakeout, cold start, hot start, and continuous operations. The target test temperature profile for the TVAC testing is provided below in Figure 3. The limits for the selected upper and lower temperatures were determined by adding margins to the safe storage and operating temperatures of various internal components. These safe storage and operating temperatures are provided in Table 2.

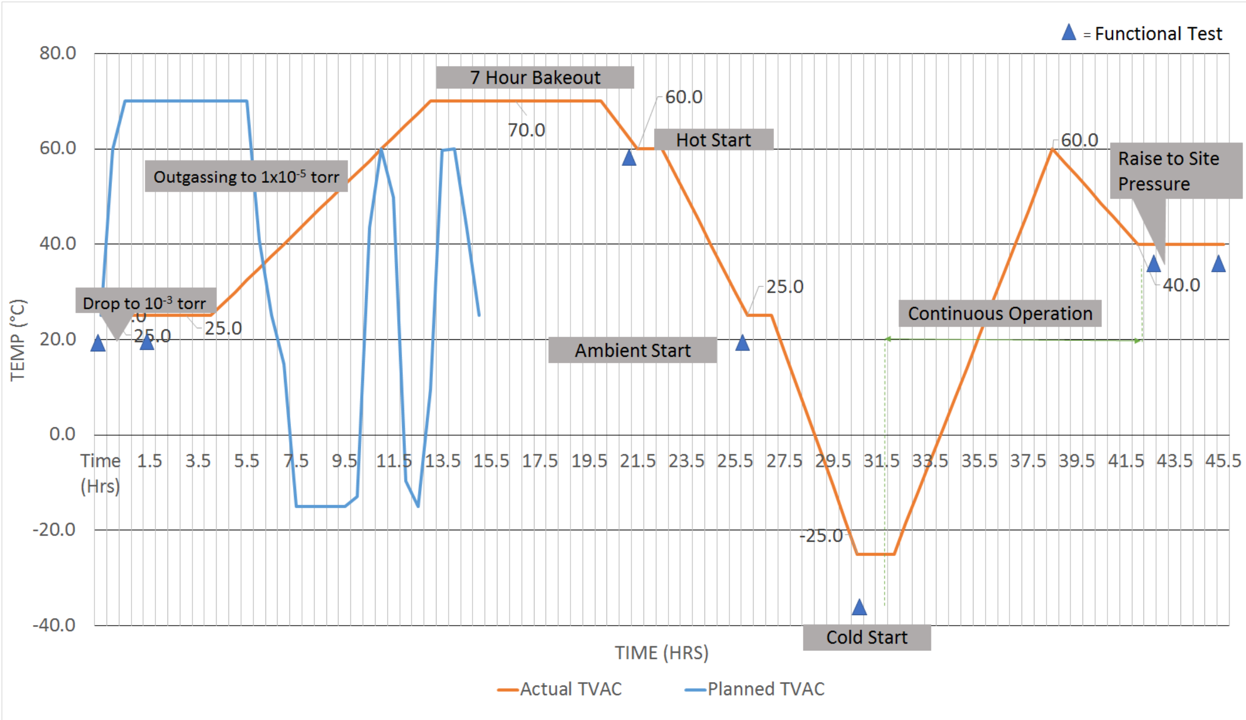

Figure 3: Planned vs Actual TVAC Thermal Profile

During all phases temperature monitoring was performed with T-type thermocouples placed in eight locations on the outside of the spacecraft and seven locations on the inside (Figure 4), this data was logged for later analysis. While AR#1 was powered on, board integrated thermal sensors were also monitored. Since STP requirements prohibit syncing excessive heat into the H6 pallet, the structure and flange became areas of interest for temperature monitoring because they act as the largest heat paths for the electronic components contained in AR#1 therefore, external thermocouples were mounted to the top, flange and each of the sides of AR#1 with a series of three thermocouples featured on the left side to better capture temperature distributions along the length of the specimen. Internal thermocouples were mounted directly to the processing units on each of the flight computers and to the two power converters on the power board and this data was displayed live to inform the test operator if component operating temperatures exceed allowable levels, requiring chamber conditions or operating procedures to be altered to bring component temperatures back into the allowable ranges.

Table 2: Safe Operating Temperatures

Component	Safe Operating Temperatures	
	Min.	Max
Xiphos Q7 [a]	-40 ˚C	85 ˚C
PicoZed 7020 [b]	-40 ˚C	85 ˚C
PicoZed 7030 [c]	-40 ˚C	85 ˚C
OEM628 GNSS [d]	-40 ˚C	85 ˚C
MAI-400 [e]	-40 ˚C	80 ˚C
GoPro Hero 4 [f]	-	52 ˚C

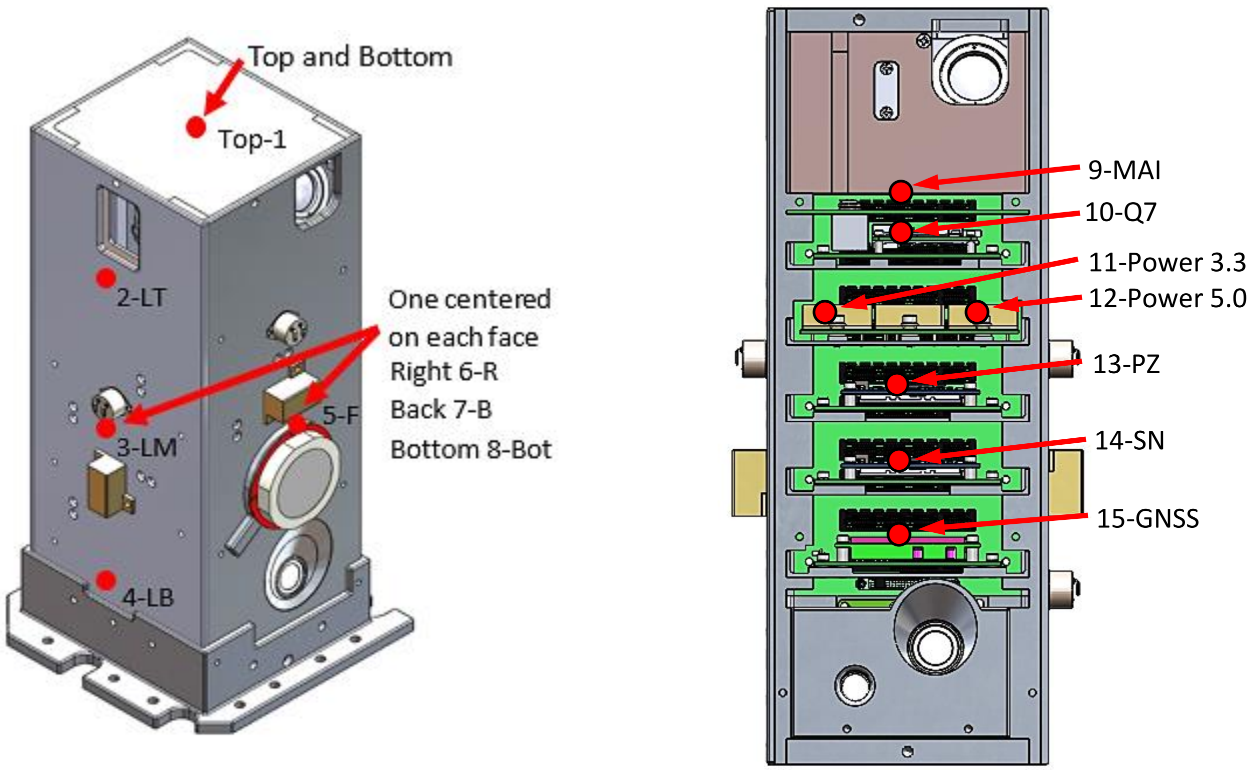

Figure 4: Thermocouple Locations

Prior to starting the TVAC test sequence, the PC clock time was noted to provide accurate timestamps for the duration of the test. Additionally all operators were required to use ground straps and gloves when handling AR#1 before, during and after testing.

The procedures for each TVAC testing phase are detailed as follows:

Pre-Test Bakeout: The pre-test bakeout was performed to outgas all materials onboard AR#1. This bakeout occurred in the same chamber as the thermal vacuum test. Before bakeout a functional test (FT) was performed. Chamber pressure was initially brought down to $1x10^{-3}$ Torr and another FT was run. As materials outgassed the chamber pressure was brought below $1x10^{-5}$ Torr and the temperature was raised to 70°C. The transition from ambient temperature (~25°C) to 70°C occurred at a rate of approximately 0.0625°C/min. Once 70°C was reached, AR#1 remained at this temperature for approximately 4 hours.

Thermal Vacuum Testing: The experiment cycled through the following test scenarios after the pre-test bakeout: Hot Start, Ambient Start, Cold Start, and Continuous Operation. In the transition stages between test and during continuous operations, the temperature was varied while at a vacuum pressure of approximately $1x10^{-5}$ Torr. Temperature stabilization preceding testing at each temperature condition was determined by the thermocouples mounted on the outside of the experiment.

Hot Start: After the bakeout process, the temperature of AR#1 was decreased to approximately 60°C. The hot start test was performed once AR#1s temperature had stabilized at 60°C. After initial power on, a FT was performed by the test operator. After performing the test, the experiment was turned off while the temperature remained at 60°C for approximately 2 hours.

Ambient Start: After the hot start, the temperature of AR#1 was decreased to ambient temperature (~25°C) at the rate of approximately 0.2°C/min. After reaching ambient temperature, AR#1 was powered on and a Functional Test (FT) was performed to verify the experiment was not damaged. After completing the FT, AR#1 was powered for approximately 2 hours.

Cold Start: AR#1s temperature was further lowered from the ambient temperature condition to -25°C. After initial power on, a functional test was performed by the test operator. After performing the test, the experiment was turned off while the temperature was kept at approximately -25°C until all heaters cycled and the maximum current draw for each heater was recorded.

Continuous Operations: Continuous operations consisted of varying temperatures from -25°C to 60°C while the experiment was powered on. Internal sensors (t-type thermocouples and AR#1 integrated) collected temperature data via the lab computers and NTS hardware. These temperatures were compared to the external temperature sensors mounted to the outside of the experiment. One cycle was performed with a maximum transition rate of 0.24°C/min.

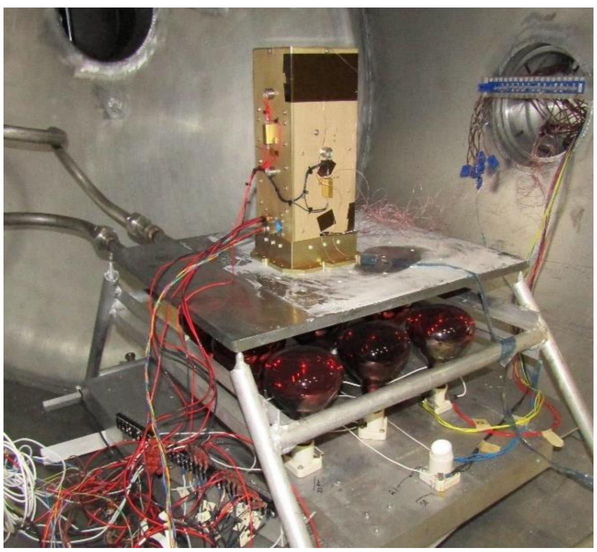

Figure 5: TVAC Test Chamber 1

TVAC Testing and Results

TVAC testing was originally scheduled for 03/21/2018 through 03/25/2018. Initially there was only going to be a single round of testing performed during TVAC that would be under vacuum, followed by a sweep through all of the selected test temperature profiles, and then a move into vibe testing. However, due to certain issues explained below, multiple TVAC testing runs were required.

During the first round of TVAC testing, the only data gathered came from the thermocouples provided to us through the NTS facility, and the singular external power supply that was supplying the payload with 28V operational power. During this first round however, the payload initially ran into some issues regarding temperatures on the PicoZed 7030. This temperature was measured off of a thermocouple placed directly on the exposed silicon die of the Zynq 7030 FPGA. This meant that the main temperature recorded was the actual IC that contained the FPGA: the most important IC on the system on module (SOM) per the project requirements. During the TVAC chamber's -25°C cold start, the PicoZed reached 50°C: in the 70°C bakeout, the PicoZed peaked at 150°C. After much discussion of probable causes of this extreme temperature, it was decided that another round of TVAC testing would be needed.

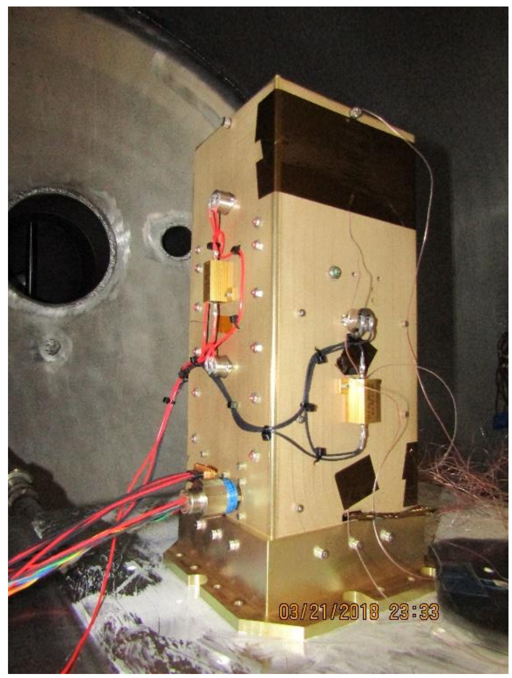

Figure 6: TVAC Test Chamber 2

During the different modes of operation in the second round of testing, the data from the flight computer was downloaded from our script into Excel to graph the data and determine the cause of the extreme temperature. The temperature was also showing similarly high on another temperature sensor that was not even attached to the same board as the PicoZed. This revealed stronger evidence that something was malfunctioning on the PicoZed than what data was coming off of the external thermocouples provided

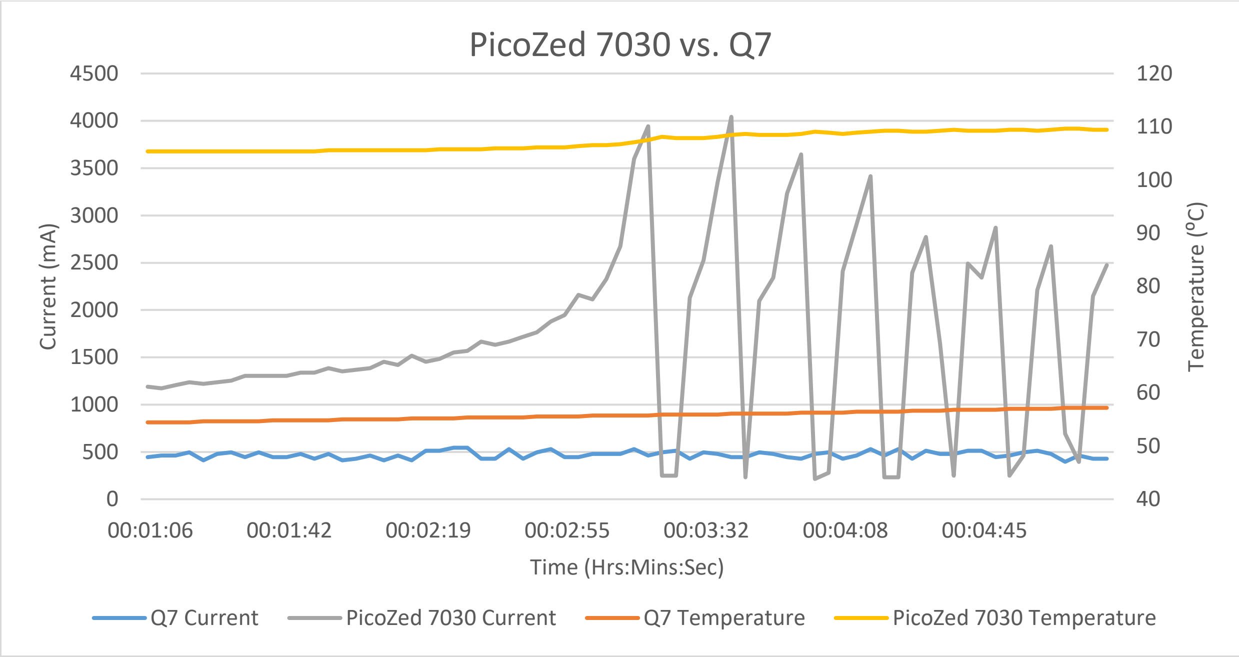

Figure 7: PicoZed vs. Q7 Current

by NTS. When the temperature was graphed against the other flight computer, the Q7, it was clear that this problem needed to be solved immediately.

Upon review, it became apparent that there was a problem with the PicoZed 7030. The current draw of the PicoZed 7030 was expected to never go over 1.5 amps. As shown, the PicoZed 7030 was exceeding 3 amps, which was causing the internal protection circuitry to turn off the power. All further TVAC testing was put on hold once this issue was identified. At this point, various options were considered how to fix the problem. One glaring fact was that the Q7 flight computer had the FPGA Zynq 7020. The PicoZed had the later model FPGA, the Zynq 7030, hence the name. It was shown that the Q7 FPGA was not overheating and not over-drawing its current. This was confusing at first because the 7020 and 7030 were nearly identical FPGAs, a main difference being that the 7030 was an exposed flip-chip ball grid array (BGA), whereas the 7020 was a "normal" style BGA where the silicon die is wire bonded internally, providing better heat transfer to the PCB. As reference, the Q7 data during the same round of testing as the PicoZed 7030 is provided in the graph above.

The decision was made to perform a third round of TVAC testing, featuring a previously unused PicoZed 7030 (without heatsink), PicoZed 7030 (with a heatsink), a PicoZed 7020, as well as the previously used power board. The heatsink used on the PicoZed 7030 was a copper heat strap attached to the mounting system of the daughter card of the PicoZed 7030 and between the FPGA of the PicoZed 7030. The TVAC testing procedure was to leave the temperature at ambient and pull the pressure down while the spacecraft was on with all computers idling. Shortly after the chamber reached near vacuum, it became apparent that the PicoZed 7030 without a heatsink was quickly reaching critical temperatures again. A small time later, the PicoZed 7030 with a heatsink started reaching critical temperatures as well, most likely having saturated the copper heatsink with too much heat. Throughout the entire test, in stark contrast to the PicoZed 7030, the PicoZed 7020 did not reach critical temperature. The PicoZed 7020 temperatures matched closely to the Q7 flight computer's temperature data from earlier testing.

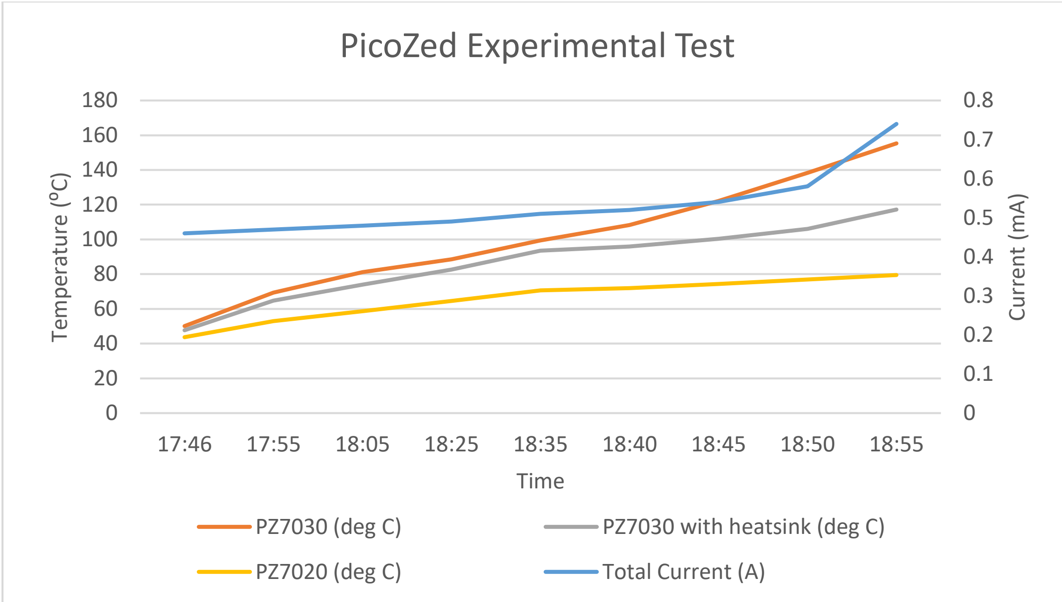

Figure 8: PicoZed Experimental Test Data

After reviewing the results of the test, the decision was made to swap the PicoZed 7030 with a PicoZed 7020. Thanks to the modular electrical and mechanical system, and the foresight to have enough on-hand, the PicoZed 7020 was integrated with the flight hardware as our secondary flight computer in a matter of minutes. After this modification was done, the rest of the boards were able to be rapidly placed back into the satellite.

A fourth and final TVAC test was performed per the original TVAC procedure to fully and finally verify that the system as a whole functioned correctly over all of the temperature ranges described by the TVAC procedure. It is notable that the PicoZed 7020 performed as it did in the previous experimental setup. The rest of the system performed nominally throughout the test and no further issues were observed. Because of this, the TVAC testing was declared complete and the system was then ready for vibe testing. The satellite was never opened again from this point forward.

TVAC Conclusions

TVAC testing yielded several lessons that validated parts of our design and exposed the need to exchange other parts. Firstly, the PicoZed 7030 thermal and current runaway indicates that this system on module (SOM) is not suitable for use in a vacuum without an appropriate method to sink heat from the processor die. This is because the die on the PicoZed 7030 is exposed and does not sink its heat into the rest of the SOM. The PicoZed 7020, however, does sink its heat into the rest of the SOM. It has the same form factor as the 7030 and is a suitable replacement.

The circumstances of the PicoZed 7030 failure also validated our circuit protections. Although the current fluctuated wildly on the PicoZed daughtercard itself, our circuit protections prevented the rest of the system from being affected. The power regulators on the daughtercard successfully disabled power when the PicoZed 7030 current reached approximately 4 Amps.

The modularity of the system was also put to the test by the need to exchange the PicoZed 7020 in place of the 7030. We were able to test multiple PicoZed configurations in a separate, identical structure due to the ability to insert any flight computer in any flight computer slot. After it was determined that we needed to replace the PicoZed, we were able to simply switch out the cards without affecting the rest of the system.

The second round of testing highlighted the benefits of having access to temperature, current, and voltage data for each subsystem. Having the software that gave us this data allowed us to diagnose that the PicoZed was at fault. After the PicoZed replacement, the system operated successfully in the subsequent testing cycle. This demonstrated that the system can survive in a vacuum at the range of temperatures tested. This elevated the TRL of the COTS components in the system to level 5.

Vibration Test Overview

Space Test Program (STP) instructed the team to perform a vibration test on the flight equipment. The goal of this test was to identify any latent defects and manufacturing flaws in electrical, electromechanical, and mechanical hardware at the system level. STP mandated that the system be tested to the following requirements as listed in their Interface Control Document, shown in Table 3.

Table 3: STP Random Vibration Test Spectrum

Pre-Delivery Random Vibration Test Spectrum					
	Duration = 60 seconds				
	PI Launch Axis Test Spectrum				
	Freq (Hz)	PSD (G^2/Hz)	dB	AREA	Grms
	20	0.040	*	*	*
	80	0.040	0.00	2.40	*
	500	0.040	0.00	16.80	*
	2000	0.010	-1.00	27.73	6.85
	PI Lateral Axis Test Spectrum				
	Freq (Hz)	PSD (G^2/Hz)	dB	AREA	Grms
	20	0.010	*	*	*
	80	0.040	1.00	1.50	*
	500	0.040	0.00	16.80	*
	2000	0.010	-1.00	27.73	6.67

Based on the requirements laid out by STP and several conversations with STP and NTS, the ACES RED team created a Vibe Test Plan. This document included an overview of the system, as well as the STP requirements, test procedure, and safety and handling instructions. The following is the test procedure prescribed in the official test plan and presented at the Test Readiness Review.

Prior to transport of the test article to the testing facility, we performed an initial functional test. Next the test article was mounted on the vibration table for the X-axis tests. The Pre-Sine Sweep, Random, and Post-Sine Sweep were performed as described in Figure 9: AR#1 Vibe Test Procedure , and the test article was removed for inspection. During review, the vibration table was

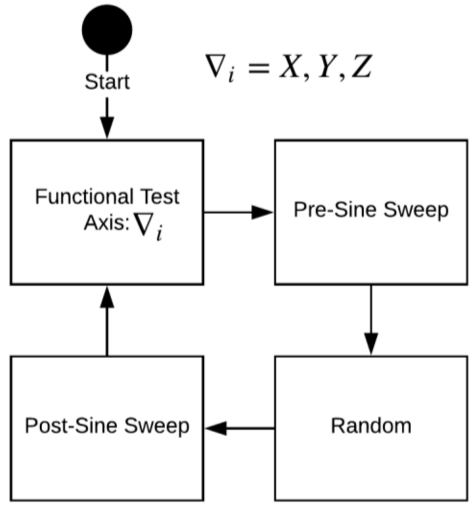

Figure 9: AR#1 Vibe Test Procedure

setup for the Y-axis tests. The same procedure was followed for the remaining Y and Z axes with functional tests being run in between.

Vibe Testing and Results

Two rounds of vibration testing were performed on the ACES RED flight unit. Both of the rounds were performed in identical fashions following the vibe test plan. The first round was intended to be a qualification test before the experiment was shipped onward to Houston, but the flight unit had to be opened up after TVAC to fix issues that came up in that testing. Therefore, the flight unit had to be re-qualified to show that nothing had changed in the configuration or quality of the assembly.

Technicians at National Testing Service (NTS) located in Huntsville, AL performed the vibration tests in their dynamics lab. The test engineer handling the ACES RED project machined a mounting plate to interface between the AR#1 flange and the surface of the vibe table. Installation of the experiment onto the vibe table entailed fastening the mounting plate to the vibe table then the flight unit onto the mounting plate. The only ways in which the execution of the vibe test deviated from the original plan was that the order of the axes tested was not X, Y, Z but instead Y, Z, X and the sine sweeps were specified to be performed up and down between 20Hz and 2000Hz. This was because the vibe table was already in the horizontal testing configuration when we arrived, so it was more efficient to test both of the axes parallel

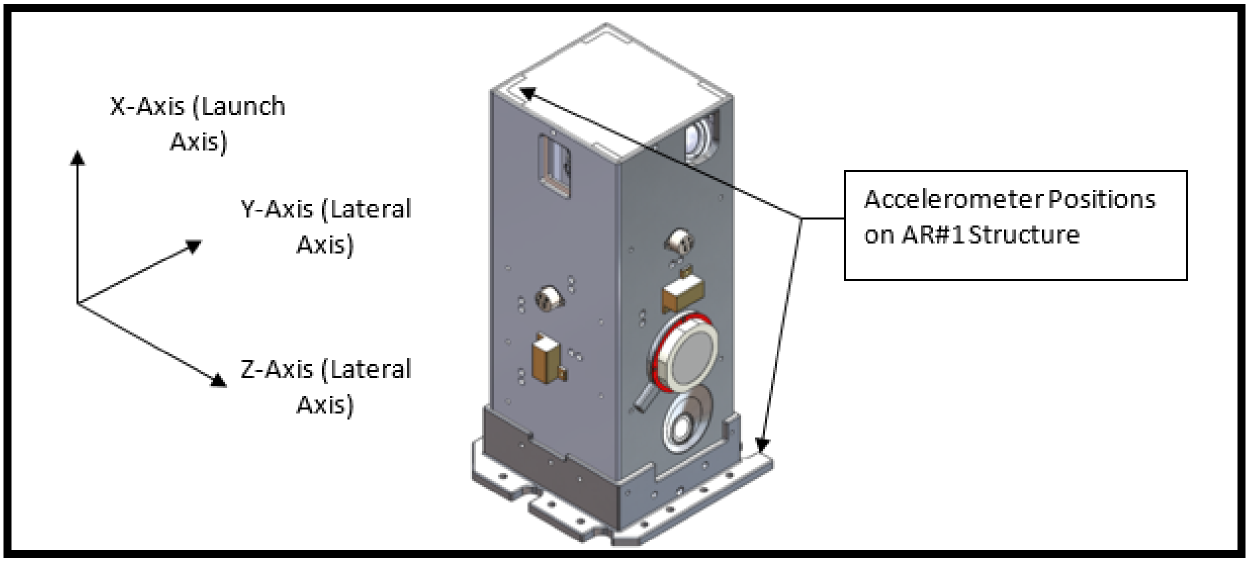

Figure 10: Testing Axes and Accelerometer Positions

to the ground and then flip the vibe table to test the last axis.

Once the experiment was installed on the vibe table, two tri-axis accelerometers provided by NTS were affixed on the top and bottom (on opposite faces) of the flight unit. This was achieved by placing a piece of Kapton tape on the AR#1 structure then using a quick-drying glue to stick the accelerometers onto the tape. The locations of the accelerometers are shown in the Figure 10.

While the accelerometers were being installed and the NTS testing workstation set up, the AR#1 team ran an aliveness, full-functionality, and STP interface test to make sure that the experiment had not been damaged in transport and was still completely functional.

After the NTS technician and the AR#1 team indicated that their equipment was functioning as expected, all of the loose wires were staked down to the flight unit, the mounting plate, or to the vibe table itself in such a way that they could not shake independently of the test configuration and affect the outcome of the test in any measurable way.

The vibe test began with the Y-axis by performing a 0.5G sine sweep up and down between 20Hz and 2000Hz at a rate of 0.5-1 octave/minute. Then random vibrations lasted for a minute after the applied spectrum reached 0 db and was followed by another identical sine sweep. After that axis was complete, the AR#1 team conducted a visual inspection and connected to the experiment to perform another set of aliveness, full-functionality, and STP Interface tests. Once those were passed, the mounting plate was unscrewed, spun, and re-attached to the vibe table in order to test the Z-axis. This axis followed the same pattern and passed its electrical testing. Then the vibe table was disconnected from the vibration drum and the drum was flipped 90 degrees so that a circular plate could be placed on top. The mounting plate with AR#1 still attached were placed on the new plate and screwed into position (as shown below). Then the X-axis (launch axis) was tested in the same way as the previous two axes. At the conclusion of the vibe test, the experiment again passed the electrical testing.

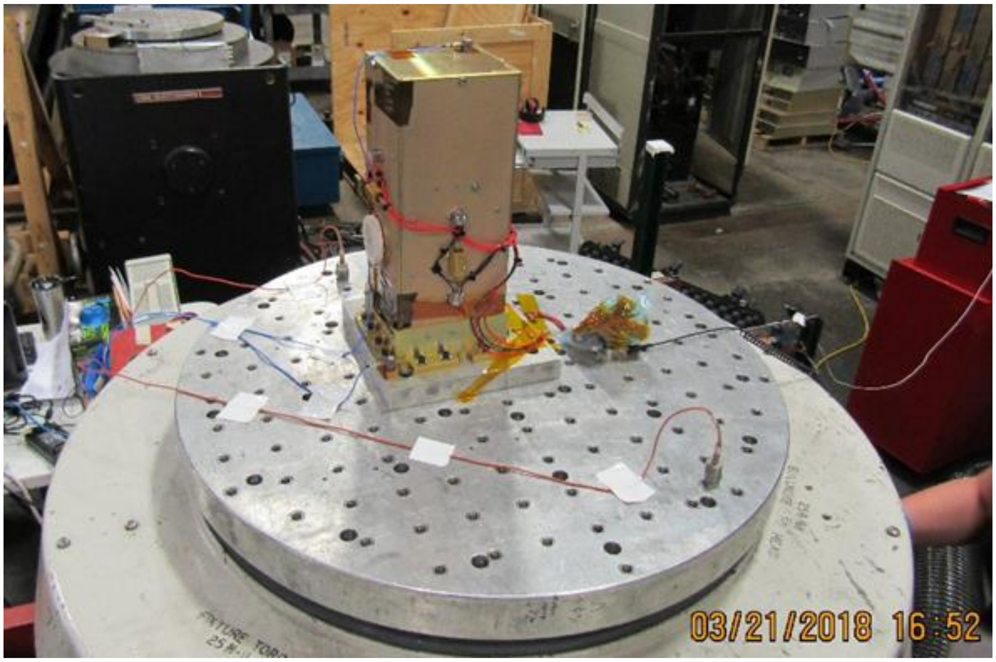

Figure 11: X-Axis Vibe Test Configuration

Vibe Conclusions

ACES RED #1 performed nominally during vibe testing. Aliveness and functional tests were successfully conducted before and after each axis. Visual inspections after each axis showed that the experiment did not receive any visible damage. Preliminary analysis of the data as it was received showed that the experiment had frequency levels that would be nominal for launch. No excessive deformations were seen during or after the test. The ACES RED #1 modular structure and contained hardware met NASA STP (Space Test Program) vibration requirements for acceptance and integration onto the STP-H6 payload pallet.

Overall Conclusions

With a completed and documented demonstration in flight-like conditions (i.e. "a relevant environment"), we have achieved TRL designation of 5 for the hardware in this experiment. During the TVAC testing, we saw an immediate benefit to our reconfigurable design architecture. Fortunately, through contingency planning and risk mitigation strategies utilizing our modular and reconfigurable design, we had alternatives in place during our testing phase. We were able to swap the PicoZed 7030 with the PicoZed 7020 which gave us significant science data to support leveraging the Zynq FPGA in a space environment. Although seemingly a negative result, this allowed us to continue to progress the experiment, by verifying the survival of the 7020 as an alternative processor. The big success is that our modular design has paid off allowing us to be able to reconfigure during testing and continue on without significant downtime. The modularity of the design also allows us to leverage the same data bus architecture on any given hardware provided it can be interfaced leveraging our interface control.

Additionally, our tray-based design met the workmanship level NASA requirements for launch. The payload is currently undergoing integrated vibe testing with the other experiments on the STP-H6 pallet and preliminary results are showing further success.

Lessons Learned

Many strategies, approaches, and best practices from this project have been gleaned that will be able to be carried forward to the next iteration of the program. Listing them all would be outside of the scope of this paper, however, some of them include things like leveraging a team that includes both contractors and government employees working side-by-side in the lab. This may be the single most valuable lesson to carry forward for future programs. As compared to the hands-off type approach of passing on requirements to contractors and having them develop a system in relative isolation ultimately leads to a product that 1) does not meet requirements, 2) is excessive in cost, and 3) cannot be completed in a timely manner.

Leveraging industry standards and naming conventions can save a significant amount of time and can better refine processes and procedures. Another lesson is that beginning communication for integration early and continuing to discuss it often can make for a much more seamless transition into that phase of the project. Also leveraging early prototypes, time permitting, can alleviate many design issues seen too late in the process to mitigate against.

Future Work

After having achieved this level of performance, the next steps include continued testing of AR#1 to ensure proper hardware and software integration to the associated interfaces followed by an on-orbit demonstration of the hardware. Additionally, development of the ground station software as well as any software updates to the flight hardware are still planned prior to integrated testing with the Space Test Program Houston office in the coming months.

The follow-on project will leverage the modular tray-based design. Additionally, depending on the final TRL achieved for other aspects of the design, including flight computers and subsystems, those may be utilized as well.

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